https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

Resolving the Technosphere

Eric Galbraith[1], Abdullah-Al Faisal[1], Tanya Matitia[1], William Fajzel[1], Ian Hatton[1], Helmut Haberl[2], Fridolin Krausmann[2], and Dominik Wiedenhofer[2]

[1]Earth and Planetary Sciences, McGill University, Montreal, Canada
[2]Institute of Social Ecology, BOKU University, Vienna, Austria

Correspondence: Eric Galbraith (eric.galbraith@mcgill.ca)

Abstract. The global assemblage of human-created buildings, infrastructure, machinery and other artifacts has been called the 'technosphere', and plays a major role in the present-day dynamics of the Earth system. It enables the rapid extraction and processing of materials from other spheres, combusts fossil fuels causing climate change, and transports materials and people across the planet surface. It provides a vast range of services to humans, such as supporting the production of food, shelter, long-distance communication, and entertainment. However, Earth system science has been slow to explicitly incorporate the technosphere as an integrated part of its conceptual and quantitative frameworks. Here we propose a refined definition of the technosphere, intended to assist in developing functional integration with other Earth system spheres, and an End-Use Technosphere categorization, EUTEC, that is theoretically aligned with human activities and wellbeing. The formal definition and resolved categorization enable basic attributes of the technosphere to be delineated, including its mass distribution among components and in space, as well as its temporal dynamics. In particular, of the roughly 1 Tt of technosphere mass, we estimate that one third is comprised of residential buildings and one third by the transportation system, both of which we map at one-degree resolution. Moreover, we show that reconstructions of technosphere mass since 1900 follow exponential growth with long-run growth rates of $>3\%\ \mathrm{y}^{-1}$, consistent with autocatalytic behaviour, allowing it to become an ever-more dominant component of the Earth system. The quantitative understanding of the technosphere remains rudimentary, and is in great need of further work to better integrate it with Earth system science.

1 Introduction

More than 8 billion humans live on Earth, embedded within a massive network of roads, buildings, vehicles, machinery and other artifacts that spans the globe. The entirety of these human creations, arrayed across the surface of our planet as well as orbiting above it, has often been referred to as the 'technosphere'. Humans construct and maintain the technosphere to provide end uses such as transport, comfortable living spaces and communication, and are also entirely dependent on it to keep us alive - we could not provide more than a few million humans with food, drinking water, or shelter without it (Fischer-Kowalski and Weisz, 1999; Smil, 2004).

The use of the term technosphere has been justified by the fact that these human creations can be considered a large and complex functional aggregate, like other spheres of the Earth system (Table 1). Like the atmosphere, in which convection at one location can be strongly linked to precipitation at a distant location a week later, components of the technosphere are

Sphere	Description
Lithosphere	The planetary crust, composed of a continuous sphere of rock, underlain by the mantle.
Pedosphere	The mixture of non-living solid materials that lies on top of the lithosphere, including the inorganic and organic components of soils and marine sediments.
Atmosphere	The layer of gas that envelopes the Earth, including suspended solutes and particles, bounded by outer space.
Hydrosphere	Liquid and solid phases of water comprising the ocean, lakes and rivers, groundwater, permafrost, snowpack and glaciers, including solutes and entrained particles.
Biosphere	All living organisms, from unicellular bacteria to whales, including humans and domesticated animals.
Technosphere	All non-food matter extracted from other spheres of the Earth system and transformed to novel states that achieve end-uses intended by humans.

Table 1. Conceptualizing the spheres of the Earth system including the technosphere, defined according to the matter of which they are comprised.

involved in many globally-interconnected internal processes. For example, the functions of mining machinery are strongly linked to transportation networks, metal processing facilities and manufacturing plants. Like the biosphere, the technosphere has autocatalytic features, supporting its own growth over time by increasing the rate at which materials can be extracted, processed, transported, and transformed to final products (Herrmann-Pillath, 2018). In addition, it represents a significant component of the Earth surface. Depending on how it is defined, the technosphere has been estimated to be of comparable scale to the biosphere, both in terms of its mass and the fluxes it enables: for example, the mass of human creations has recently exceeded the dry mass of all living organisms (roughly 1100 Gt dry mass) (Elhacham et al., 2020), the rate of primary energy conversion within the technosphere is roughly half that of terrestrial above-ground net primary production (roughly 20 TW) (Haberl et al., 2007) and continues to increase (Smil, 1991; Lenton et al., 2016), and the rate of mass dislocation at the Earth surface by machines (roughly 320 Gt y^{-1}) exceeds all natural geomorphological processes by an order of magnitude (Cooper et al., 2018). There seems little doubt that, at this point, the technosphere can be considered a major component of the Earth system.

Yet despite its importance, the technosphere remains absent from most conceptions of Earth system science (Herrmann-Pillath, 2018). The term is inconsistently defined, lacks a system of categorization, and its basic attributes have not been holistically assessed, including its mass distribution and temporal dynamics. Industrial ecology and ecological economics have made great strides in estimating the fluxes of material and energy through the global technosphere, under the names industrial metabolism or socioeconomic metabolism research (Graedel et al., 2015; Weisz et al., 2015; Pauliuk and Hertwich, 2015; Haberl et al., 2019; Lanau et al., 2019; Fu et al., 2022). However, so far there have been few efforts to integrate this work with the Earth system science perspectives. In short, the understanding of what the technosphere is, as an Earth system component, remains remarkably poorly resolved.

The remainder of this paper aims to contribute to the study of the technosphere by reviewing and proposing a refinement of its definition, presenting an end-use categorization scheme, assessing its composition, providing preliminary maps of its first-order distribution across the Earth surface, and discussing basic empirical features of its temporal dynamics. We aim to contribute to building an interdisciplinary foundation for linking the material composition of the technosphere with its functionality, its associated energy and material fluxes, its interactions with the remainder of the Earth system, and its contributions to human wellbeing, as informed by multiple fields of research.

2 Defining the boundaries of the technosphere

The term ‘technosphere’ has been attributed to science writer Wil Lepkowski, who apparently first used it in a 1960 article (Otter, 2022). It was subsequently used by systems engineer John Milsum (Milsum, 1968) and, the following year, by biologist Julian Huxley in a reflection on the first moon landing (Huxley and Nicholson, 1969; Otter, 2022). More recently, geologist Peter Haff has promoted the term to encapsulate the global proliferation of human technology at the heart of the concept of the Anthropocene (Haff, 2014). Haff described the technosphere as including "everything that enables rapid extraction from the Earth of large quantities of free energy, long-distance, nearly instantaneous communication, rapid long-distance energy and mass transport, high-intensity industrial and manufacturing operations, and a myriad additional ‘artificial’ or ‘non-natural’ processes without which modern civilization could not exist". His use of ‘technosphere’ was chosen rather than ‘anthroposphere’ to suggest a detached view of an emerging geological process that has entrained humans, rather than one that has humans exclusively at the centre. Zalasiewicz (2017) used a slightly modified version of this definition, specifying the part of the technosphere which is currently in use. The in-use portion of the technosphere is also distinguished by Johansson 2013, and is generally equivalent to commonly used terms in industrial ecology, including ‘in-use stocks’ (Pauliuk and Hertwich, 2015), ‘material stocks’ (Haberl et al., 2019), ‘manufactured capital’ (Weisz et al., 2015) and ‘technomass’ (Inostroza, 2014), as well as ‘artefacts’ in the early socio-ecological literature drawing on ecological anthropology (Fischer-Kowalski and Weisz, 1999). Throughout the years, the technosphere has been defined in many different ways, sometimes including human-disturbed soils, or even ideas.

Here, we propose a refined definition of the technosphere which is compatible with the standard Earth system spheres conceptualization (Table 1). We follow the Earth system science convention of defining a sphere in terms of the nature of the matter of which it is comprised, rather than in terms of specific processes or fluxes. In other words, to use the terminology common among industrial ecology and ecological economics, a sphere is defined as an assemblage of stocks, not according to flows. For example, the atmosphere is defined as the envelope of gas that surrounds our planet, including tiny particles suspended within it – there are many processes that occur within the atmosphere, such as convection, precipitation and cloud formation, but these do not define the atmosphere. We also strive to create a clear distinction from the Earth system spheres with which the technosphere interacts, so as to avoid overlooking or double-counting components.

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

To these ends, the technosphere is here defined as: *all non-food matter extracted from other spheres of the Earth system and transformed to novel states that achieve end-uses intended by humans*. We highlight four important distinctions inherent in this definition.

First, we limit the components of the technosphere to nonliving creations. As such we do not include living humans or any other life form within the technosphere, but instead consider all living organisms as components of the biosphere (where the biosphere is the sum of all organisms). This provides long-term continuity with Earth history, since humans were clearly a part of the biosphere in the ancient past, as were the ancestors of our domestic animals, and there was no point at which we 'left' the biosphere. Our food continues to be derived almost entirely from the living organisms that comprise the biosphere, with whom we also share viruses and bacteria, and we ourselves are living organisms now as much as we ever were. Thus, the definition here considers broiler chickens, grapefruit, oil palms, corn and genetically-modified sheep as part of the biosphere, while pacemakers and prosthetic limbs are considered part of the technosphere. Also, we do not include modifications of the pedosphere or lithosphere as part of the technosphere, thus excluding the soils of croplands and rubble of mines, all of which would remain classified in the pedosphere. This definition avoids conflating the technosphere with the meaning of 'artificial', a conflation which easily occurs with the term 'anthroposphere' (Pauliuk and Hertwich, 2015) and which promulgates a false dichotomy between the natural and artificial worlds. Because of these exclusions, the technosphere definition proposed here implies a much smaller mass than that estimated with the definition proposed by Zalasiewicz (2017), which was dominated by human-disrupted soils and sediments.

Second, because the technosphere refers exclusively to non-living physical matter, it does not include human activities or mental constructs like institutions, corporations, or social norms. In addition to providing a more unambiguous definition, this separation of human activity from the technosphere preserves the independence of human agency, which was identified by Donges (2017) as a conceptual problem with the technosphere of Haff (2014).

Third, we draw a boundary where the state of an in-use component ceases to be fit to serve an intended end-use, given the allocated amount of maintenance activity. This boundary is often subject to social characteristics that determine the willingness or ability to maintain or repurpose items, but is nonetheless observationally quite easy to identify. As such, an object that undergoes repair remains in the technosphere, while an object that is discarded or irreparably damaged is not. This can be seen as analogous to the definition of the biosphere as comprised exclusively of living organisms – when an organism dies, it ceases to be part of the biosphere.

Fourth, this definition of the technosphere does not include mass that would be called 'waste'. Although the idea of waste is clearly important for humans, sustainable development, and the Earth system, a precise definition that works on long timescales is difficult to construct. Most of what would be considered technosphere waste is gradually transformed or mixed across the Earth system on timescales from hours to millennia, making it difficult to define a boundary at which it would ever stop being waste. Furthermore, biological analogs of technosphere waste are not typically considered part of the biosphere in Earth system science. For example, exhaled CO_2 is part of the atmosphere, while dissolved organic molecules in seawater are part of the hydrosphere, and the carbonate shells of foraminifara accumulated in sediments are part of the pedosphere. Placing the boundary in this way captures the fact that abandoned components of the technosphere are inexorably re-incorporated into

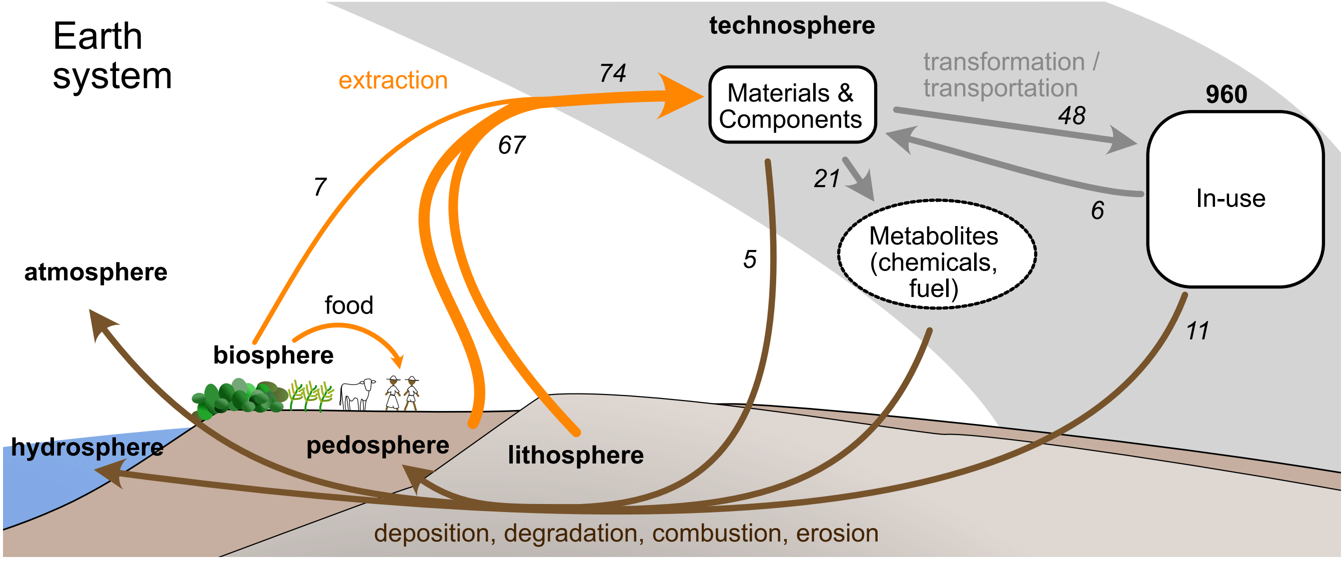


Figure 1. Schematic of the Earth system including the technosphere. Italicized numbers show fluxes in Gty^{-1}, bold number shows the in-use mass in Gt as estimated by Krausmann et al. 2018 for the year 2015.

the other spheres, rather than remaining apart. A discarded soda can on the soil interacts with its surroundings as part of the pedosphere, microplastics in the ocean are consumed by plankton as part of the hydrosphere, and polychlorinated biphenyls incorporated into living organisms are part of the biosphere. The flux of matter through the technosphere has introduced many novel chemicals and structures that are now distributed throughout the other spheres of the Earth system, and have fundamentally changed our planet, just as the flux of oxygen from the biosphere changed the redox state of the Earth surface billions of years ago (Lenton et al., 2016).

As illustrated in Figure 1, we distinguish the in-use portion of the technosphere from substances that have been extracted or produced from Earth system materials, but remain in an intermediate state, as well as those that are used in a way that causes them to be chemically transformed in a single use. We refer to the latter as technosphere metabolites, by analogy with the molecules that are transformed within organisms to provide metabolic energy and fuel growth. The technosphere metabolites include fuels (fossil fuels, firewood, bio-ethanol, uranium ore), industrial chemicals (reagents, fertilizers and pesticides) and pharmaceuticals. As noted above, food – the organic matter produced by organismal growth and consumed by living humans – remains within the biosphere.

We also note that this definition of the technosphere is equivalent to the in-use material stocks of socio-ecological metabolism research (Fischer-Kowalski and Weisz, 1999; Haberl et al., 2019), after excluding human bodies and domesticated animals (since the Earth system framework places all of these within the biosphere). This provides a consistency with economy-wide Material Flow Analysis (ew-MFA, see below) which is helpful for estimating fluxes (Krausmann et al., 2017a; UNEP, 2016).

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

3 Categorizing the technosphere

Our interest here is to understand the technosphere as a dynamic, interacting, physical component of the Earth system, created because of socially-coordinated human motivations to produce specific outcomes that are supported through its existence and use. A systematic categorization of the entities that comprise the technosphere, such as that provided for the biosphere centuries ago (Linnaeus, 1758), can provide a conceptual basis for its description, and can help identify relationships within it.

Extensive classification systems of human creations already exist, largely developed by economists and business entities to organize commerce and develop trade statistics. For example, the central product classification (CPC), developed by the United Nations (United Nations. Statistical Division, 2004) provides an exhaustive and exclusive categorization of traded goods and services – the outputs of economic activity. The CPC consists of more than 4000 classes, nested within a 5-level hierarchical classification. However, these categories are designed to apply to economic data, rather than a physical systems understanding of technosphere function within the Earth system. As a result, many classes are specific to materials or manufacturing sectors, or include intermediate components, and these are frequently mixed together. For example, one category includes “Medical appliances, precision and optical instruments, watches and clocks”, which aggregate a wide range of end uses based on the technical nature of manufacturing. Similarly, “Tools, tool bodies, tool handles, broom or brush bodies and handles, boot or shoe lasts and trees, of wood” lumps together diverse intermediate components with final goods, presumably based on the commonality that all are made of wood. The CPC also frequently focuses on details of consumer goods, with specific categories such as "Dolls representing human beings; toys representing animals or non-human creatures", while all industrial buildings are included in a single category.

Another relevant set of categorizations has been used within the framework of economy-wide material flow accounting (ew-MFA), for the purpose of monitoring the biophysical basis of society and informing sustainable resource use policies (Krausmann et al., 2017a; UNEP, 2016). The ew-MFA framework is widely used to provide policy-relevant indicators in the Sustainable Development Goals and for national resource policies, consistently accounting for all fluxes in physical units. This accounting draws on data using the CPC classifications and other socio-economic statistical data sources such as the Food and Agriculture Organization, International Energy Agency and United States Geological Survey, and currently reports annual raw material extraction and physical trade between economies, as well as the material footprint, i.e. all upstream material use along supply chains whose products are ultimately destined for consumption elsewhere (Wiedmann et al., 2015; Lenzen et al., 2022; UNEP). Recent developments in ew-MFA have provided the first fully mass-balanced accounts of the global socio-metabolic system including raw material extraction and in-use material stocks, as well as all waste and emissions (Krausmann et al., 2018). Work within this framework has primarily categorized fluxes and in-use stocks by their material properties, or focused only on specific end uses within a subset of the technosphere (Chen and Graedel, 2015; Lanau et al., 2019; Streeck et al., 2023), although Wiedenhofer et al. (submitted) have recently proposed a grouping of global material stocks into 13 end-use categories.

We propose here a novel categorization that is intended to provide an improved mechanistic understanding of the technosphere, as well as integration with Earth system processes. The categorization is deliberately aligned with end uses, for two reasons. First, human end-use outcomes are what motivates the existence of the technosphere - every component of the technosphere was motivated by at least one type of intended end use. Second, end-uses are mechanistically linked to material impacts on the Earth system, including energy transformations, mass transport, biosphere modification, and chemical processes. Thus, an end-use based categorization connects naturally to Earth system outcomes. Because the technosphere is intimately entwined with human activities, our categorization is also aligned with a classification of human activities in order to help mechanistically link the technosphere to activities. We call the categorization the End-Use TEchnosphere Classification, EUTEC. The EUTEC is intended to provide an exhaustive and exclusive set of categories for the in-use technosphere, i.e. extracted materials that have been transformed into the state intended for use, and persist in a usable state.

Our classification follows the following principles:

1. The relevant end-use is that which motivated the production of the thing. For example, the production of a television is motivated by the desire to provide experiences to viewers, rather than a desire to convert electrical energy to electromagnetic radiation for its own sake.
2. A single category can include both fixed, immovable creations (i.e. elements of the built environment) as well as movable artifacts, where they both contribute to the same type of outcome. For example, the end use ‘processing of metals’ can include machinery as well as constructed refining facilities.
3. The material of which something is comprised does not influence the end-use classification. A jacket is classified in the same way, whether the material is derived of petroleum (nylon), plants (cotton), or animals (leather). Electronics are considered a particular collection of materials, rather than an end use.
4. Recreational use (i.e. exclusively to provide desired experiences) is only considered if there is no other clear end-use. For example, snowmobiles are classified as vehicles.

3.1 High level categories

Most of our categories associate technosphere components with the human activities they specifically support through their end use. However, we identified a number of human creations which do not clearly support or modify the outcomes of specific activities, but instead change the background context in which humans spend their time, or contribute non-specifically to diverse activities by interacting with human neural processes through symbolic information. This led to the following three high-level categories.

1. *Ambient Context.* This part of the technosphere alters the physical environment that humans inhabit, without otherwise engaging with human activities to produce physical outcomes. It generally exists to provide humans with a more comfortable, attractive, or otherwise desirable immediate environment. Modification of the ambient context allows humans to inhabit climates that would otherwise be too hot or too cold for our physiology, and frequently carries important cultural or social status implications. It includes buildings for residence, as well as other buildings that are not dedicated to a specific activity by their structure, but instead simply provide a comfortable or attractive environment. Thus, it includes

many of the buildings used for office work or commerce, but excludes specialized transportation buildings such as warehouses and airports, and industrial buildings such as factories, refineries and power plants. It also includes the machinery and devices that condition the interior environments of these spaces, such as for heating, cooling and lighting, and all furnishings. Clothing and accessories are also included here, as they modify the ambient context for human bodies.

2. *Informational.* Devices, artifacts and infrastructure that support the recording, transfer/communication, processing, and storage of symbolic information. Symbolic information can be construed as physical patterns that are somehow generated through an interface with humans or the world, which may be written words and numbers, or electrical impulses representing strings of zeros and ones. These play essential roles in human societies, by externalizing and preserving thoughts, providing high quality communication (Boyd, 2018), enabling complex logical operations and computation, and providing neural stimulation. The informational category includes all devices for recording, storing, processing, transmitting, and transforming symbolic information to sensory input. Information can be stored in many forms, including as engravings on stelae, words on paper, or magnetized particles in solid-state electronics. This stored information can be processed, transported, or observed by humans at a later time, and can also serve as an internal process within technosphere function, allowing automation and robotics. Common modern forms of information storage include accounting data printed on paper, novels printed as books, visual recordings on magnetic tape, and recorded music stored as files in flash drives. Transmitting includes radio antennae, fiber optic cables, and communications satellites.

3. *Activity-specific.* The remainder of the technosphere can be linked to specific human activities. These entities operate in direct support of (or in place of) activities in a way that materially alters the outcomes of the activities. These activity-modifiers might accelerate the outcomes of an activity with which they are engaged, and/or change the nature of the product of the activity. This includes vehicles and infrastructure that contribute to the physical transportation of people and non-human goods and materials, the machinery and tools that humans use to construct the technosphere, and the provision of energy. The distinctions within this category are aligned directly with the Motivating Outcome-Oriented General Activity Lexicon (MOOGAL) (Galbraith et al., 2022; Fajzel et al., 2023), which provides an exhaustive and exclusive categorization of human activities using physically-based outcome descriptions.

The three categories and their components are listed in Table 2, and a decision tree to mitigate ambiguity in classification is provided in Appendix Figure A1.

Level 1	Level 2	Level 3	Description
Ambient context	Residential & service buildings	Residential & service buildings	Buildings that provide comfortable spaces for humans without being functionally engaged in specific activities.
	Somatic comfort & decoration	Environmental conditioning	Heating/cooling devices to maintain ambient spaces at more comfortable temperature and/or humidity.

		Furnishings	Movable objects intended to make inhabited environments more comfortable and/or more attractive.
		Apparel	All clothing & footwear, including for babies, sports.
Informational	Informational	Storage	Artifacts that record and retain symbolic information in a persistent form.
		Information processing	Devices that transform information to generate novel information ouputs.
		Communications infrastructure	Devices and infrastructure that transport information spatially, including integrated input and output.
Activity-specific	Food provision	Food growth & collection	Machinery, buildings and infrastructure to assist in the growth of edible organisms and their harvesting.
		Food processing	Machinery and buildings for transforming food, including preservation for storage and distribution.
		Food preparation	Equipment for final preparation of food immediately prior to consumption, usually carried out at home or in a restaurant.
	Technosphere creation & maintenance	Extraction	Machinery, equipment, buildings and infrastructure for extracting materials from the biosphere, pedosphere and lithosphere.
		Materials processing	Materials and chemical processing facilities including refineries, furnaces.
		Energy provision	Energy conversion, electricity transmission (outside buildings) and storage.
		Artifact creation and maintenance	Machinery, tools, equipment and factories to aid in the creation and maintenance of the technosphere.
		Construction	Machinery, equipment and tools for creating buildings and fixed infrastructure.
	Transportation	Surfaces	Artificial surfaces to facilitate and accelerate wheeled transport, including roads and rail.
		Vehicles	Devices for transporting passengers and cargo on land.

	Aircraft	Flying devices for transporting passengers and cargo through the atmosphere.
	Aquatic vessels	Ships and boats for transporting passengers and cargo in marine or freshwater.
	Packaging, storage and logistics	Specialized buildings, infrastructure and containers for loading/unloading and storage.
	Pipelines	Tubes for transporting fluids over long distances.
Maintenance of surroundings	Inhabited environment maintenance	Domestic appliances, devices and tools not related to food preparation.
	Water control & supply	Infrastructure, machinery and buildings for controlling the flow of water, accumulation in reservoirs, distribution to end-users and potability.
	Waste management	Sewage infrastructure, landfill and incinerator machinery, recycling facilities.
Organization	Access	Buildings and devices to help developing norms and enforcing or modifying access rights.
	Force	Weapons, buildings, vehicles and vessels supporting the threat or enactment of physical violence and associated logistics.
Deliberate neural restructuring	Deliberate neural restructuring	Non-informational equipment and buildings specialized for teaching, religious activities and research.
Experience-oriented	Active recreation	Sports equipment, outdoor recreation gear, sport and recreation facilities, amusement parks.
	Interactive stimulus	Non-informational devices that are used interactively to produce desired experiences.

Table 2: The EUTEC end-use categorization.

4 Basic attributes of the technosphere

Given the formal definition and categorization adopted above, we are now in a position to characterize the basic features of the technosphere in a holistic, exhaustive and exclusive manner.

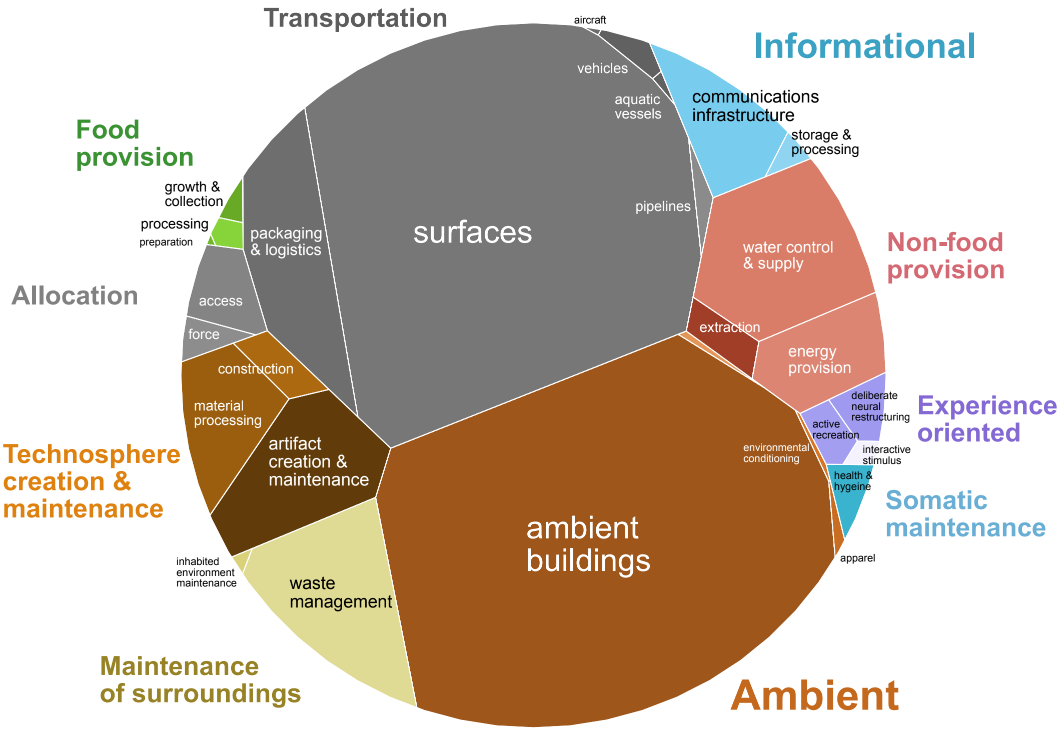


Figure 2. Approximate distribution of mass among technosphere end-use categories. The area of each coloured region is proportional to its mass. The uncertainties for many of the smaller categories are a factor of 2 to 5, mostly due to lack of observational constraints on the distribution of mass among non-residential buildings and infrastructure. See Appendix B for estimation methodology.

4.1 Distribution of mass within the technosphere

First we provide an overview of how the mass of the technosphere is partitioned among the EUTEC categories and across the planet surface, circa year 2019. The total mass of the technosphere, as estimated by Krausmann et al. (2018) and extrapolated by Elhacham et al. (2020) was 1100 Gt in 2019. The overall mass of technosphere components is not necessarily the most relevant thing for Earth system interactions – for example, the extraction and processing of some elements, such as gold, can have large environmental impacts even for small masses – however, it is a very straightforward way to understand the physical scale of the technosphere's main components.

4.1.1 Contributions of EUTEC categories to total mass

As described in Appendix B, we combine estimates from Wiedenhofer et al. (submitted), which are derived from the dynamic Material Inputs Stocks and Outputs version 2 (MISO2) model, with bottom-up estimates from Matitia (2022) and multiple other sources to quantify a subset of technosphere components. We emphasize the fact that many of these estimates are very poorly constrained. Global studies of in-use material stocks have only been available for a little over a decade (Rauch, 2009;

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

Müller et al., 2013; Glöser et al., 2013) and uncertainties frequently exceed a factor of 3 (Lanau et al., 2019). In particular, the mass of materials in specialized buildings and heavy machinery is very poorly documented, and the masses of large public infrastructures such as dams and sewer systems are not typically available. Even for residential buildings, substantial disagreement exists in the literature. As a result, these estimates should be seen as preliminary, and we hope that they will become better constrained through future work.

As shown in figure 2, the largest two components of the technosphere by mass are Ambient Context and Transportation. Transportation is dominated by surfaces (32% of total, comprised of roads, railroads, bridges and tunnels), associated logistical infrastructure (4% of total), vehicles and aquatic vessels (0.5% of total). The ambient context is comprised almost entirely of residential and service buildings (34 % of total mass). The Informational category, despite its prominence in human affairs and experience, accounts for only a small portion of the total mass, most of which is the communications infrastructure (poorly constrained). The other activity-specific technosphere components account, together, for roughly one quarter of the total.

4.1.2 Mapping the technosphere

We also provide, in Figure 3, an estimate of the overall spatial distribution of the two parts of the technosphere that comprise most of the mass: the ambient context buildings, and the transportation system. Together these account for an estimated two thirds of the technosphere. As detailed in Appendix C, the spatial distributions of these components are estimated from a combination of satellite observations and down-scaling of national data using surrogate local variables. The transportation system includes roads, railways, bridges and tunnels, passenger and commercial vehicles, rolling stock, commercial passenger aircraft, oil and gas pipelines, and the merchant fleet. The transportation system mass is particularly concentrated in eastern North America, Europe and East Asia.

4.2 Dynamics of the technosphere

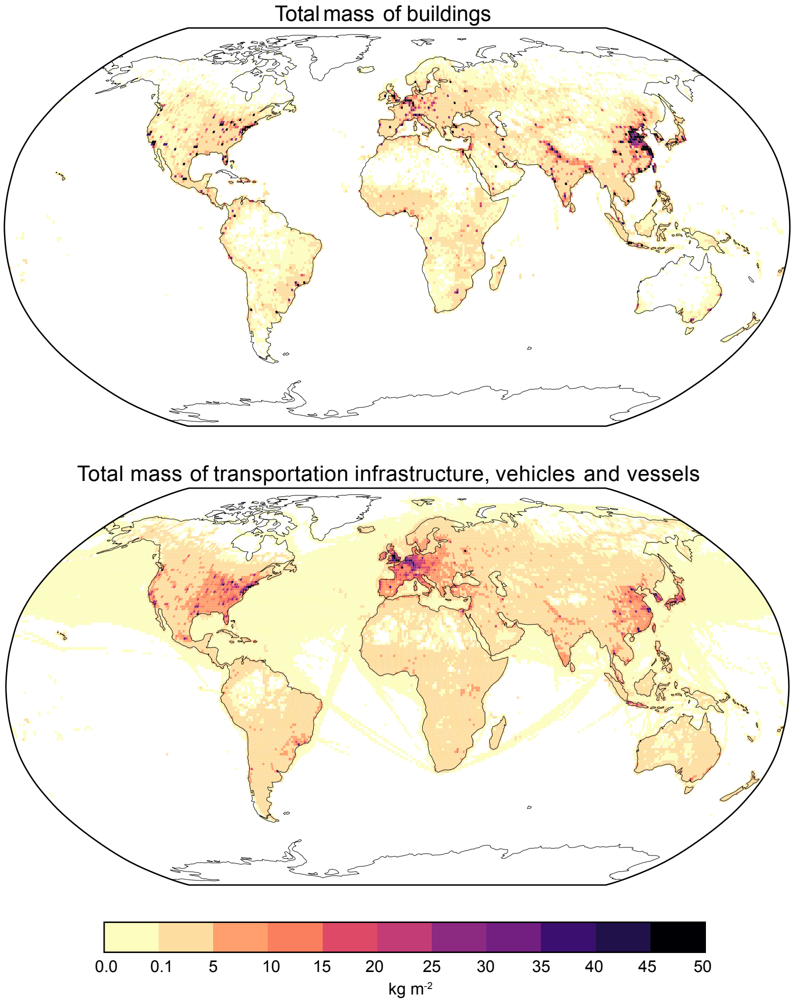
The technosphere is an extremely dynamic component of the Earth system, undergoing rapid internal transformations as well as driving large-scale changes in the rest of the Earth system, such as climate change and habitat destruction. Arguably, the earliest components of the technosphere were stone and wooden tools, roughly 3 million years ago (Otter, 2022). At that time, the global human population was likely only a few hundred thousand individuals, and the subsequent human population growth - over four orders of magnitude - has occurred symbiotically with the growth of the technosphere. Here we provide a brief discussion of how mass fluxes contribute to the growth and maintenance of the technosphere.

4.2.1 Turnover rates within the technosphere

We can assume that for some component of the technosphere, x, the mass T_x (in kg) over some domain of the Earth surface varies according to a rate of change as

$$\frac{dT_x}{dt} = m_x - \lambda_x T_x + \Gamma \tag{1}$$

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024


Total mass of buildings

Total mass of transportation infrastructure, vehicles and vessels

Figure 3. Spatial distribution of the two largest components of the technosphere by mass, at 1-degree resolution. Note that the palest yellow colour shows very low values, less than 0.1 $kg\,m^{-2}$, and a lower threshold of 0.001 $kg\,m^{-2}$ was used, below which the area is white.

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

where m_x is the rate at which T_x is manufactured (in g y^{-1}), Γ is a transport operator that transfers T_x between domains (in g y^{-1}), and λ_x is a decay rate, defined as the fraction of in-use stock that ceases to be usable by the local population each year (in units of y^{-1}). The lifetimes of components of the technosphere vary from weeks to centuries. For short lifetimes, we can assume that the effect of age cohorts is small, and the assumption of a constant lifetime will be reasonable (Van der Voet et al., 2002; Miatto et al., 2017). However for long lifetimes, proportionally large accumulation of stock can cause the age cohorts to play a major role in determining the time evolution of a stock.

4.2.2 Autocatalytic growth of the technosphere

The total technosphere has grown very rapidly over the period for which ew-MFA-based mass estimates are available, which extends back to 1900 (Krausmann et al., 2017b; Wiedenhofer et al., 2019). This rapid growth can be attributed, at least in part, to its autocatalytic properties. Autocatalysis occurs when the products of a process increase the rate of (i.e. catalyze) the same process that produced them, thereby accelerating growth as the mass increases. The production of much of the technosphere, such as extractive and processing machinery and transportation infrastructure, can directly accelerate the continued extraction and processing, thereby leading to an acceleration of overall growth.

Importantly, the autocatalytic nature of the technosphere sets it apart from the analogous creations of non-human organisms. Other organisms do modify their abiotic environments, including deliberate niche construction by animals - for example, birds build nests, beavers build dams and termites construct mounds. But although these modifications benefit their constructors, they do not catalyze their own further growth in the same way: a termite mound does not directly contribute to the construction of further termite mounds other than by helping to ensure the survival of termites. As such, the mass of these other constructions are bound tightly to the mass of their creators. The technosphere, in contrast, has grown at a far higher rate than the human population, with the ratio of technosphere mass: human mass increasing by roughly a factor of 8 over the past century (from 18 t person^{-1} to 140 t person^{-1}).

The autocatalytic character of technosphere growth can be encapsulated in a simple equation,

$$\frac{dT}{dt} = cT \tag{2}$$

where T is the mass of the technosphere (in g), and c is a coefficient (in s^{-1}) that captures the degree to which a given increment of technosphere growth accelerates its continued growth. If c is constant over time, the autocatalytic relationship produces exponential growth of T. As shown in Figure 4, the increase of technosphere mass since 1900 is indeed well approximated by an exponential with a slope of 3.6$\%y^{-1}$. Interpretation of the details of the technosphere growth rates must be made with caution, given the inherent uncertainties. The material flows of major components are modeled from sparse data, and in-use lifetime assumptions (related to the value of λ in the formulation here) are relatively simple. With those caveats in mind, it is notable that the agreement is nearly perfect since 1970, the period during which the data is likely to be most reliable compared to earlier time periods.

Prior works have discussed changes in technosphere mass fluxes over the 20th century by identifying changes that were coincident with prominent historical events (Krausmann et al., 2009; Wiedenhofer et al., 2013; Elhacham et al., 2020). Here,

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

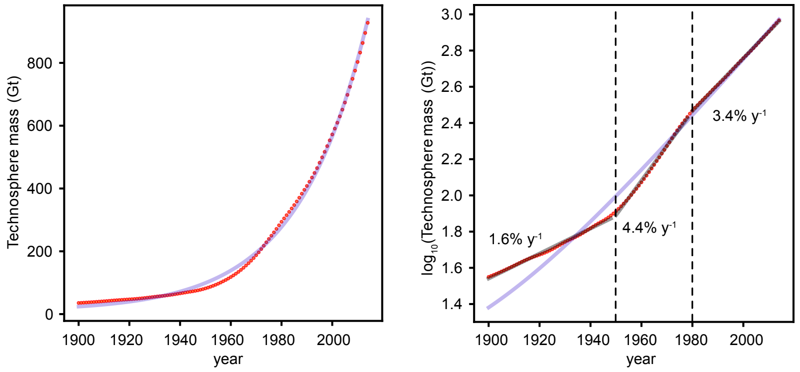


Figure 4. Growth of technosphere since 1900. Dots show estimated technosphere mass from Krausmann 2018 with humans and domesticated animals removed. The left panel is plotted on linear scales, while the right panel shows the logarithm of mass. Blue lines show an exponential fit with growth coefficient $c = 0.036$, while the three grey lines in the right panel show piecewise linear regressions with coefficients .

we take a broader view, separating the technosphere growth curve based simply on the major features of its shape. When divided into 3 segments, with divisions at 1950 and 1980, linear fits of log(T) vs. year suggest exponential rates for these three periods of 1.6%, 4.4%, and 3.4%, respectively ($r^2 > 0.995$). The sharp break in slope near 1950 is consistent with the idea of the 'Great Acceleration' following World War II (Steffen et al., 2015).

Although we do not have direct information on the size of the technosphere prior to the 20th century, it is clear that the exponential growth of 3% was not typical of long-term growth of the technosphere. For one thing, extrapolating this rate of growth backwards would imply that the technosphere had a mass of 1 t around year 1330 AD. Obviously this is incorrect, as the single great pyramid of Giza, constructed in 2600 BC, was - on its own - roughly 6 Mt. Even if the great pyramid were the only component of the technosphere in existence at that time, the average long-run rate of growth would have had to be on the order of 0.1% per year in order to arrive at the present-day mass. The present global net growth rate of the in-use technosphere (110 Mt d^{-1}) amounts to roughly 20 great pyramids per day.

5 Conclusions

The technosphere definition proposed here is intended to provide a clear and relatively unambiguous definition to help integrate the physical underpinnings of human societies within Earth system science. Socio-ecological research provides a rich body of observations that can serve as a starting point for this integration (Haberl et al., 2019). Unlike most prior categorizations of the technosphere, which were based on material types, the EUTEC introduced here is based on the end-uses that motivate the creation of technoshere components, in alignment with human needs and desires. By basing the majority of categories on physically-oriented activity end uses, the EUTEC can help to bridge the core features of economies and societies with Earth system processes.

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

As shown by global ew-MFA, the mass of the technosphere is dominated by buildings used to provide a comfortable ambient context for humans, and by infrastructure and vehicles used to make the relocation of humans and materials faster and more convenient. These analyses have also shown that the technosphere is composed almost entirely of geological materials: aggregate, brick, concrete, asphalt, plastic, glass and iron account for the vast majority (Krausmann et al., 2018). It is therefore predominantly a modification of lithospheric components. However, the technosphere has major impacts on the biosphere, accelerating the modification of the land surface and extraction of organic matter from the biosphere, and on the atmosphere, through the combustion of billions of tons of fossil fuels each year.

Our maps of the technosphere show the degree to which it is unevenly distributed over the Earth surface. The transportation system is particularly concentrated in Europe, eastern North America, and east Asia. Our appraisal of technosphere dynamics shows that the technosphere must have grown slowly over the Holocene, with average rates on the order of 0.1% y^{-1}. This contrasts strongly with the past century, when growth rates exceeded 3% y^{-1}. Although many factors could have contributed to this rapid growth, it appears likely that the strong autocatalytic character of the technosphere was implicated.

Future work on the technosphere could elaborate details of the material composition of different technosphere components, and the links between chemical elements within the technosphere and their Earth system sources and consequences, to build a unified understanding of how they contribute to global biogeochemical (or, perhaps, ‘technogeochemical’) cycles. Better understanding of physical constraints on the functioning of the technosphere could also help to elucidate possible pathways towards long-term sustainability, as well as identifying potential tipping points. The trillion-ton technosphere is a major component of the Earth system, and its evolution over the next century is likely to determine the future of climate – and life – for millennia to come.

Data availability. Previously published data used for the global mass estimates are summarized in Supplementary Table 1. The gridded data used for figure 4 will be provided as part of the Surface Earth System Analysis and Modeling Environment (SESAME) dataset (Faisal et al., in preparation).

Appendix A: Categorization flow chart

Appendix B: Estimation of technosphere composition by category

Constructing an estimate of the global technosphere composition by end-use remains highly challenging. Some categories are reasonably well-constrained by observations, but others are, at present, strongly limited by data availability. Our goal here is to provide an overview of the existing estimates as a starting point for future work, and to use them to provide current best estimates for all categories, which are necessarily highly uncertain. Because buildings comprise a large part of the total mass and contribute to many EUTEC categories, we discuss them first before proceeding to the other categories.

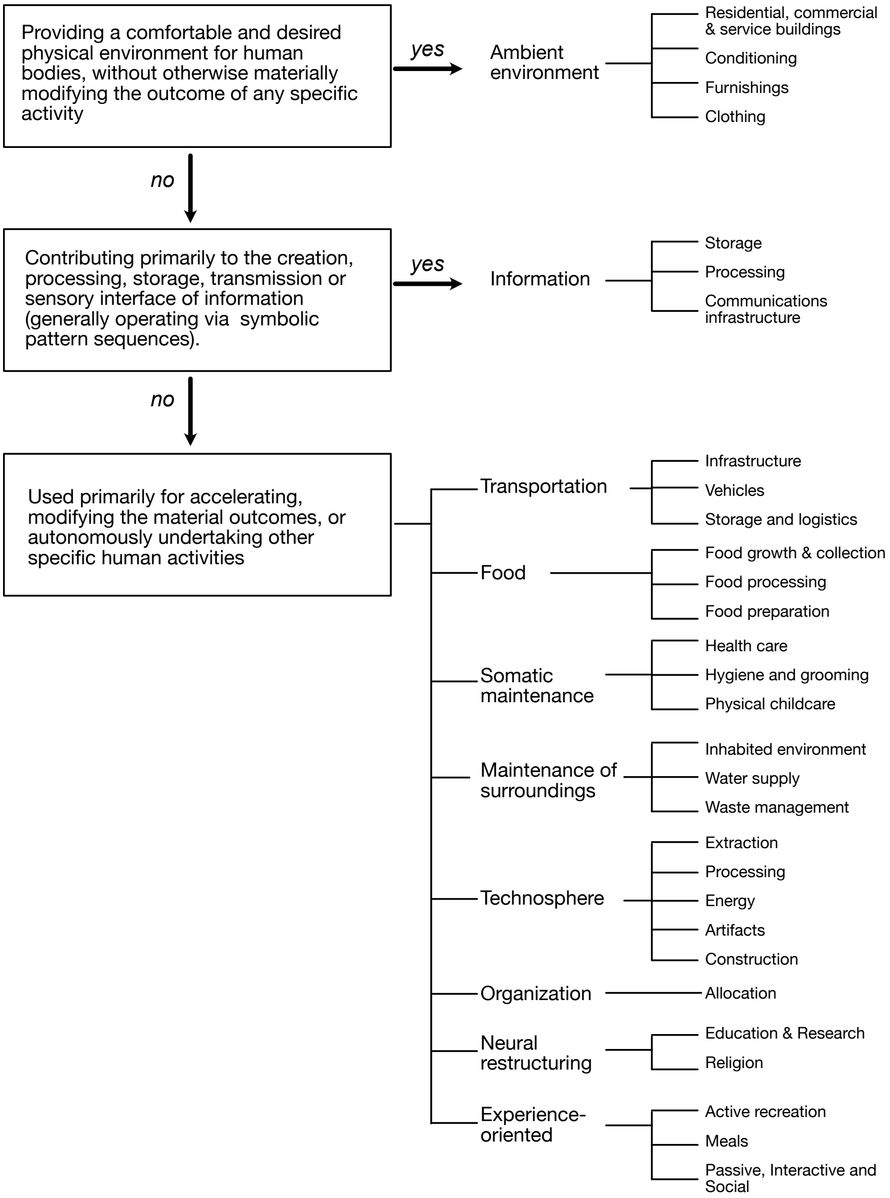


Figure A1. Logical flow chart for assigning technosphere components among the three high-level categories.

B1 Buildings

We draw on three sources for global building mass.

Haberl et al. (submitted) provide an estimate of building mass drawing on satellite observations of building volume (Esch et al., 2022) to which they apply geographically-variable material intensities (i.e. masses of material per building volume). The total estimated stocks for year 2019 are 547 Gt (+/- 25%), of which 474 Gt are associated with residential use, 33 Gt with non-residential use, and 41 Gt associated with either residential or non-residential use. It should be noted that the residential vs. non-residential identification is methodologically challenging and should be seen as approximate.

Deetman et al. (2020) estimated building stocks based on a regression model of reported floor areas, interpolated across regions, and simulated over time with a dynamic stock model. Their model differentiates residential from service buildings, but explicitly left out industrial and agricultural buildings, simply saying that it was very hard.

The MISO2 model (Wiedenhofer et al., 2021) provides ew-MFA-derived stock estimates for 13 categories, 2 of which are buildings. MISO2 estimates for buildings are divided between residential and non-residential, and suggest a total of 524 Gt in year 2021. Unfortunately, as for other estimates, the industrial, agricultural and other specialized non-residential building masses are unconstrained.

We take Deetman's estimate for dominantly ambient environment service buildings (offices, retail and shops, hotels and restaurants) of 15 Gt, and assume the remaining 33 Gt of service buildings are more specialized to specific activities (e.g. schools, hospitals, public transportation, assembly buildings). Adding this ambient service building total to the residential building arrive at a total ambient building stock of 364 Gt, with a roughly factor of 1.5 uncertainty.

We aim for overall consistency between estimates by assuming the difference between the ambient building stock and the MISO2 total is accounted for by specialized non-ambient buildings, totalling 160 Gt, of which 33 Gt is non-industrial and non-agricultural. This suggests 127 Gt of industrial and agricultural buildings, roughly 1/4 of the total building stock. This is a highly uncertain value, and could be wrong by at least a factor of 2, which we hope can be addressed in future work. We then make a weakly-informed estimate of how this industrial building mass is distributed across the EUTEC categories, to which we assign an uncertainty range of a factor of 3.

B2 Other categories

Because MISO2 provides a consistent, mass-balanced estimate that includes the entire technosphere, we use it as an overarching framework by relating the 11 non-building categories of MISO2 to the EUTEC categories. The largest uncertainty arises from the category 'Civil engineering except roads', due to its large mass (242 Gt) and diverse contents. For each of the 11 MISO2 categories, the total was partitioned among the EUTEC categories as described in the notes. Uncertainties tend to be large, with estimated ranges commonly 3 to 5. These estimates were supplemented additionally as follows.

For transportation surfaces, we used the global estimate of 314 Gt in year 2021 from Wiedenhofer et al. (2024) of all roads and railway infrastructure, including tunnels and bridges, constructed with archetypal material intensities applied to Open

Street Maps data. We take the average of this estimate and the similar estimate of Matitia (2022) which also included CIA World Factbook road length estimates and applied slightly different material intensities.

The energy category includes fossil fuel infrastructure as well as electricity production and distribution infrastructure. The mass of electrical grids, transformers and power plants was taken from Kalt et al. (2021) as 10.4 Gt. The estimated fraction from MISO2 civil engineering is significantly larger (total 56 Gt) to account for aggregate in large hydroelectric dams, as well as fossil fuel extraction and refining infrastructure, with significant uncertainty (range factor 4).

We used bottom-up estimates from Matitia (2022) for agricultural tractors, passenger and commercial vehicles, rolling stock, the global merchant fleet, aircraft, military vehicles and weapons. The agricultural tractors and vehicles were interpolated to missing countries using a random forest model with GDP and population as predictors. We also used Matitia (2022) estimates for textiles, and the plastic components of furniture, electronics and health equipment as lower bounds on the corresponding categories.

Appendix C: Estimating spatial distribution

The spatial distribution of some technosphere components can be observed directly, such as roads (Wiedenhofer et al., 2024). However, most technosphere mass estimates are only available on a jurisdictional basis, with a single value per country. To develop a harmonized, spatially-gridded raster dataset from jurisdiction-level data, our strategy is to employ the widely used dasymetric mapping downscaling method (Mennis, 2003). The dasymetric method allocates data from jurisdictions to 1-degree grid-cells by using appropriate variables (referred to as surrogate variables). The jurisdictional data is distributed throughout the jurisdictional domain in proportion to the surrogate variable distribution. Thus, estimating the distribution for each category of technosphere mass requires an estimate of the value per country, and a surrogate variable to use for dasymetric redistribution.

C1 Agricultural machinery

Agricultural machinery data was collected from 1999 to 2009 for 124 countries, focusing on 4W and 2W tractors provided by FAOSTAT, as well as combines (Matitia, 2022). The average horsepower for 4W tractors was determined using John Deere and Caterpillar products, whereas 2W tractor and combine horsepower were calculated using previous studies and global product averages (Ademiluyi et al., 2007). Steel mass was estimated at 85% for tractors and combines, and 50% for 2W tractors. Because the data has significant gaps, a random forest machine learning algorithm was used to fill those gaps. GDP, total population, crop production, harvested area, percentage of urban population, year, and income class were used as predictors for machinery mass data. The country-level machinery mass data was dasymetrically mapped using cropland area as a surrogate variable. Cropland area data was collected from MODIS Terra Aqua Land Cover Types (Friedl and Sulla-Menashe, 2022).

C2 Aircraft

Commercial aircraft data was sourced from the Central Intelligence Agency (CIA) factbook. The average material composition of an aircraft was determined by taking the geometric mean of material intensities for five types of commercial aircraft as reported in Jemiolo (2015). The country level airplane mass data was proportionally distributed on airport counts per grid cell. The airport locations were obtained from http://ourairports.com. The ratio of plane capacities among these airport types is difficult to quantify precisely without specific data, as it can vary greatly depending on a variety of factors such as the size and layout of the airport, the type and size of the aircraft it serves, and its operating procedures. We make a rough estimate based on general characteristics of these airport types, such that Seaplane Base : Small Airport : Medium Airport : Large Airport = 1 : 5 : 30 : 100.

C3 Merchant fleet

Country level merchant fleet data were obtained from United Nation Conference on Trade and Development (UNCTAD). Matitia (2022) utilized UNCTAD data to analyze per-country gross tonnage for five ship categories from 2011 to 2020, focusing on vessels with a gross tonnage of 11,000 tons and above. Steel mass per gross tonnage for these vessels was sourced from Kong et al. (2022). Because operational merchant ships are rarely in their home port, and are usually in transit, we dasymetrically mapped the global fleet mass using global shipping traffic density data.

C4 Building material stock

Matitia (2022) complied country level building material stock data from Deetman et al. (2020) and Marinova et al. (2020). The Global Human Settlement Layer built-up volumes (Pesaresi and Politis, 2023) served as the surrogate variable in this case.

C5 Oil and gas pipelines

Oil and as gas pipeline data was collected from Sabbatino (2018). The oil and gas pipelines were converted from line to grids based on sum of pipeline length per pixel. For the physical characteristics of the pipelines, an outer diameter of 89 cm and a thickness of 1.9 cm were assumed, both derived from Bai and Bai (2014). Pipeline materials were assumed to have an average density of steel equivalent to 7,900 kg/m^3.

C6 Rolling stock

The data for the number of registered locomotives, railcars, wagons, and train coaches were collected from a report of Union International des Chemins de Fer (UIC) and their data portal. The mass and material content of various rolling stock types were averaged from previously-published estiamtes (Delogu et al., 2017; Harvey, 2022; Kaewunruen and Rungskunroch, 2019). The country level rolling stock data was distributed proportionally to the railway densities, where the density data was collected from Global railways (WFP SDI-T - Logistics Database) at https://data.humdata.org/dataset/global-railways.

C7 Land vehicles

The International Organization of Motor Vehicle Manufacturers (OICA) provided the information of registered passenger cars and commercial vehicles worldwide from 2005 to 2015. Passenger cars were categorized into large and small groups, with approximately 30.21% classified as "large" based on global new SUV registrations. Commercial vehicles encompass light commercial vehicles (LCVs), heavy trucks, buses, and coaches. It was assumed that the ratio of trailers to truck tractors is 1.5:1 globally, with estimates of 1.4:1 in Europe and 3:1 in North America (Matitia, 2022). We employed three distinct random forest models for passenger vehicles, commercial vehicles, and trailers. These models aimed to estimate the number of vehicles per capita for countries and years where such data were missing. Predictor variables included GDP per capita, total road length, urban population percentage, and the year of analysis. All three models demonstrated a high level of accuracy, with test r^2 values exceeding 0.94, indicating robust predictive performance for vehicles across the specified categories. Material composition of the vehicles are estimated based on total curb weight. Steel, cast iron, plastic composites, aluminum, rubber, glass, and copper are comprised on 80% of a vehicle's total curb weight. Characteristics and intensities of various materials are defined from various sources such as the GREET 2.7 model, a life-cycle analysis of U.S. light-duty vehicles, and lifecycle inventory studies. Finally, the country-level vehicle mass was distributed assuming that 5% of vehicles remained on the road , and thus distributed based on road density (Meijer et al., 2018) while the remaining 95% of vehicle data was distributed based on population density (Bondarenko, 2018).

Author contributions. EDG: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review and editing, Visualization. AF: Investigation, Data curation, Writing - review and editing. TM: Methodology, Investigation, Data curation. WF: Methodology, Writing - review and editing. IH: Visualization, Writing - review and editing. HH: Writing - review and editing. FK: Data curation, Writing - review and editing. DW: Methodology, Data curation, Writing - review and editing.

Competing interests. The authors declare no competing interests.

Acknowledgements. We thank Ben Goldstein for insightful discussions. This project was supported by the Canada Research Chairs Program fund number CRC-2020-00108 and the Natural Science and Engineering Research Council (NSERC) Discovery Grant RGPIN-2020-04889. HH and DW gratefuly acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme MAT_STOCKS, grant agreement No 741950.

References

Ademiluyi, YS., Ani, O., Ugwuishiwu, BO., and Oyelade, OA.: Performance Assessment of Two-Wheel Tractor on a Loamy Sand Soil of Ilorin, Nigerian Journal of Technology, 26, 59–66, 2007.

Bai, Q. and Bai, Y.: Subsea Pipeline Design, Analysis, and Installation, Gulf Professional Publishing, 2014.

Bondarenko, M.: Global 1km Population, 2018.

Boyd, R.: A Different Kind of Animal: How Culture Transformed Our Species, Princeton University Press, 2018.

Chen, W.-Q. and Graedel, TE.: In-Use Product Stocks Link Manufactured Capital to Natural Capital, Proceedings of the national academy of sciences, 112, 6265–6270, 2015.

Cooper, A. H., Brown, T. J., Price, S. J., Ford, J. R., and Waters, C. N.: Humans Are the Most Significant Global Geomorphological Driving Force of the 21st Century, The Anthropocene Review, 5, 222–229, 2018.

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., and Heijungs, R.: Modelling Global Material Stocks and Flows for Residential and Service Sector Buildings towards 2050, Journal of Cleaner Production, 245, 118 658, 2020.

Delogu, M., Del Pero, F., Berzi, L., Pierini, M., and Bonaffini, D.: End-of-Life in the Railway Sector: Analysis of Recyclability and Recoverability for Different Vehicle Case Studies, Waste management, 60, 439–450, 2017.

Donges, J. F., Winkelmann, R., Lucht, W., Cornell, S. E., Dyke, J. G., Rockström, J., Heitzig, J., and Schellnhuber, H. J.: Closing the Loop: Reconnecting Human Dynamics to Earth System Science, The Anthropocene Review, 4, 151–157, 2017.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y. M., and Milo, R.: Global Human-Made Mass Exceeds All Living Biomass, Nature, 588, 442–444, 2020.

Esch, T., Brzoska, E., Dech, S., Leutner, B., Palacios-Lopez, D., Metz-Marconcini, A., Marconcini, M., Roth, A., and Zeidler, J.: World Settlement Footprint 3D-A First Three-Dimensional Survey of the Global Building Stock, Remote sensing of environment, 270, 112 877, 2022.

Fajzel, W., Galbraith, E. D., Barrington-Leigh, C., Charmes, J., Frie, E., Hatton, I., Le Mézo, P., Milo, R., Minor, K., and Wan, X.: The Global Human Day, Proceedings of the National Academy of Sciences, 120, e2219564 120, 2023.

Fischer-Kowalski, M. and Weisz, H.: Society as Hybrid between Material and Symbolic Realms: Toward a Theoretical Framework of Society-Nature Interaction, Advances in human ecology, 8, 215–252, 1999.

Friedl, M. and Sulla-Menashe, D.: MODIS/Terra+ Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V061, NASA EOSDIS Land Processes DAAC, 2022.

Fu, C., Zhang, Y., Deng, T., and Daigo, I.: The Evolution of Material Stock Research: From Exploring to Rising to Hot Studies, Journal of Industrial Ecology, 26, 462–476, 2022.

Galbraith, E., Fajzel, W., Xu, S., Xia, V., Frie, E., Barrington-Leigh, C., and Reyes-García, V.: Interdisciplinary Applications of Human Time Use with Generalized Lexicons, PloS one, 17, e0270 583, 2022.

Glöser, S., Soulier, M., and Tercero Espinoza, L. A.: Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation, Environmental science & technology, 47, 6564–6572, 2013.

Graedel, T. E., Harper, E. M., Nassar, N. T., and Reck, B. K.: On the Materials Basis of Modern Society, Proceedings of the National Academy of Sciences, 112, 6295–6300, 2015.

Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., and Fischer-Kowalski, M.: Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems, Proceedings of the National Academy of Sciences, 104, 12 942–12 947, 2007.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D. B., and Fischer-Kowalski, M.: Contributions of Sociometabolic Research to Sustainability Science, Nature Sustainability, 2, 173–184, 2019.

Haberl, H., Baumgart, A., Zeidler, J., Schug, F., Palacios-Lopez, D., Fishman, T., Peled, Y., Cai, B., Virág, D., Hostert, P., Wiedenhofer, D., and Esch, T.: Weighing the Global Built Environment: High Resolution Mapping and Quantification of Material Stocks in Buildings, Journal of Industrial Ecology, submitted.

Haff, P.: Technology as a Geological Phenomenon: Implications for Human Well-Being, Geological Society, London, Special Publications, 395, 301–309, 2014.

Harvey, L. D.: Reconciling Global Iron and Steel Mass Flow Datasets, with an Update to 2011-2015 and an Assessment of Uncertainty in Global End-of-Life Scrap Flow, Resources, Conservation and Recycling, 182, 106 281, 2022.

Herrmann-Pillath, C.: The Case for a New Discipline: Technosphere Science, Ecological Economics, 149, 212–225, 2018.

Huxley, J. and Nicholson, M.: Man's Deteriorating Environment, Times, p. 8, 1969.

Inostroza, L.: Measuring Urban Ecosystem Functions through 'Technomass'—A Novel Indicator to Assess Urban Metabolism, Ecological Indicators, 42, 10–19, 2014.

Jemiolo, W.: Life Cycle Assessment of Current Aned Future Passenger Air Transport in Switzerland, Ph.D. thesis, Universitetet i Nordland, 2015.

Johansson, N., Krook, J., Eklund, M., and Berglund, B.: An Integrated Review of Concepts and Initiatives for Mining the Technosphere: Towards a New Taxonomy, Journal of Cleaner Production, 55, 35–44, 2013.

Kaewunruen, S. and Rungskunroch, P.: A Through-Life Evaluation of End-of-Life Rolling Stocks Considering Asset Recycling, Energy Recovering, and Financial Benefit, Journal of cleaner production, 212, 1008–1024, 2019.

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., and Haberl, H.: Material Stocks in Global Electricity Infrastructures–an Empirical Analysis of the Power Sector's Stock-Flow-Service Nexus, Resources, Conservation and Recycling, 173, 105 723, 2021.

Kong, X., Feng, K., Wang, P., Wan, Z., Lin, L., Zhang, N., and Li, J.: Steel Stocks and Flows of Global Merchant Fleets as Material Base of International Trade from 1980 to 2050, Global Environmental Change, 73, 102 493, 2022.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H., and Fischer-Kowalski, M.: Growth in Global Materials Use, GDP and Population during the 20th Century, Ecological economics, 68, 2696–2705, 2009.

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., and Jackson, T.: Material Flow Accounting: Measuring Global Material Use for Sustainable Development, Annual Review of Environment and Resources, 42, 647–675, 2017a.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., and Haberl, H.: Global Socioeconomic Material Stocks Rise 23-Fold over the 20th Century and Require Half of Annual Resource Use, Proceedings of the National Academy of Sciences, 114, 1880–1885, 2017b.

Krausmann, F., Lauk, C., Haas, W., and Wiedenhofer, D.: From Resource Extraction to Outflows of Wastes and Emissions: The Socioeconomic Metabolism of the Global Economy, 1900–2015, Global Environmental Change, 52, 131–140, 2018.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., and Ehlert, C.: Taking Stock of Built Environment Stock Studies: Progress and Prospects, Environmental Science & Technology, 53, 8499–8515, https://doi.org/10.1021/acs.est.8b06652, 2019.

Lenton, T. M., Pichler, P.-P., and Weisz, H.: Revolutions in Energy Input and Material Cycling in Earth History and Human History, Earth System Dynamics, 7, 353–370, 2016.

Lenzen, M., Geschke, A., West, J., Fry, J., Malik, A., Giljum, S., Milà i Canals, L., Piñero, P., Lutter, S., and Wiedmann, T.: Implementing the Material Footprint to Measure Progress towards Sustainable Development Goals 8 and 12, Nature Sustainability, 5, 157–166, 2022.

Linnaeus, C.: Systema Naturae, vol. 1, Stockholm Laurentii Salvii, 1758.

Marinova, S., Deetman, S., van der Voet, E., and Daioglou, V.: Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970-2050, Journal of Cleaner Production, 247, 119 146, 2020.

Matitia, T.: Global End-Use Inventory of the Anthropogenic Mass, MSc, McGill University, Montreal, QC, 2022.

Meijer, J. R., Huijbregts, M. A., Schotten, K. C., and Schipper, A. M.: Global Patterns of Current and Future Road Infrastructure, Environmental Research Letters, 13, 064 006, 2018.

Mennis, J.: Generating Surface Models of Population Using Dasymetric Mapping∗, The Professional Geographer, 55, 31–42, https://doi.org/10.1111/0033-0124.10042, 2003.

Miatto, A., Schandl, H., and Tanikawa, H.: How Important Are Realistic Building Lifespan Assumptions for Material Stock and Demolition Waste Accounts?, Resources, Conservation and Recycling, 122, 143–154, 2017.

Milsum, J. H.: The Technosphere, the Biosphere, the Sociosphere Their Systems Modeling and Optimization, IEEE Spectrum, 5, 76–82, 1968.

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., and Brattebø, H.: Carbon Emissions of Infrastructure Development, Environmental science & technology, 47, 11 739–11 746, 2013.

Otter, C.: Socializing the Technosphere, Technology and Culture, 63, 953–978, 2022.

Pauliuk, S. and Hertwich, E. G.: Socioeconomic Metabolism as Paradigm for Studying the Biophysical Basis of Human Societies, Ecological Economics, 119, 83–93, 2015.

Pesaresi, M. and Politis, P.: GHS-BUILT-V R2023A - GHS Built-up Volume Grids Derived from Joint Assessment of Sentinel2, Landsat, and Global DEM Data, Multitemporal (1975-2030), https://doi.org/10.2905/AB2F107A-03CD-47A3-85E5-139D8EC63283, 2023.

Rauch, J. N.: Global Mapping of Al, Cu, Fe, and Zn in-Use Stocks and in-Ground Resources, Proceedings of the National Academy of Sciences, 106, 18 920–18 925, 2009.

Sabbatino, M.: Global Oil & Gas Features Database, Tech. rep., National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV . . . , 2018.

Smil, V.: General Energetics: Energy in the Biosphere and Civilization, vol. 369, Wiley, New York, NY, 1991.

Smil, V.: Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production, MIT press, 2004.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., and De Wit, C. A.: Planetary Boundaries: Guiding Human Development on a Changing Planet, science, 347, 1259 855, 2015.

Streeck, J., Pauliuk, S., Wieland, H., and Wiedenhofer, D.: A Review of Methods to Trace Material Flows into Final Products in Dynamic Material Flow Analysis: From Industry Shipments in Physical Units to Monetary Input–Output Tables, Part 1, Journal of Industrial Ecology, 27, 436–456, 2023.

UNEP: United Nations Environment Programme, International Resource Panel, Global Material Flows Database.

UNEP: Global Material Flows and Resource Productivity: Assessment Report for the UNEP International Resource Panel., Tech. rep., United Nations Environment Programme, 2016.

United Nations. Statistical Division: Central Product Classification (CPC): Version 1.1, 77, United Nations Publications, 2004.

https://doi.org/10.5194/egusphere-2024-1133
Preprint. Discussion started: 8 May 2024

Van der Voet, E., Kleijn, R., Huele, R., Ishikawa, M., and Verkuijlen, E.: Predicting Future Emissions Based on Characteristics of Stocks, Ecological Economics, 41, 223–234, 2002.

Weisz, H., Suh, S., and Graedel, T. E.: Industrial Ecology: The Role of Manufactured Capital in Sustainability, Proceedings of the National Academy of Sciences, 112, 6260–6264, 2015.

Wiedenhofer, D., Rovenskaya, E., Haas, W., Krausmann, F., Pallua, I., and Fischer-Kowalski, M.: Is There a 1970s Syndrome? Analyzing Structural Breaks in the Metabolism of Industrial Economies, European Geosciences Union General Assembly 2013, EGUDivision Energy, Resources & the Environment, ERE, 40, 182–191, https://doi.org/10.1016/j.egypro.2013.08.022, 2013.

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., and Krausmann, F.: Integrating Material Stock Dynamics into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050, Ecological economics, 156, 121–133, 2019.

Wiedenhofer, D., Fishman, T., Plank, B., Miatto, A., Lauk, C., Haas, W., Haberl, H., and Krausmann, F.: Prospects for a Saturation of Humanity's Resource Use? An Analysis of Material Stocks and Flows in Nine World Regions from 1900 to 2035, Global Environmental Change, 71, 102 410, 2021.

Wiedenhofer, D., Baumgart, A., Matej, S., Virág, D., Kalt, G., Lanau, M., Tingley, D. D., Liu, Z., Guo, J., and Tanikawa, H.: Mapping and Modelling Global Mobility Infrastructure Stocks, Material Flows and Their Embodied Greenhouse Gas Emissions, Journal of Cleaner Production, 434, 139 742, 2024.

Wiedenhofer, D., Streeck, J., Wieland, H., Grammer, B., Baumgart, A., Plank, B., Helbig, C., Pauliuk, S., Haberl, H., and Krausmann, F.: From Extraction to End-Uses and Waste Management: Modelling Economy-Wide Material Cycles and Stock Dynamics around the World, Journal of Industrial Ecology, submitted.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K.: The Material Footprint of Nations, Proceedings of the national academy of sciences, 112, 6271–6276, 2015.

Zalasiewicz, J., Williams, M., Waters, C. N., Barnosky, A. D., Palmesino, J., Rönnskog, A.-S., Edgeworth, M., Neal, C., Cearreta, A., and Ellis, E. C.: Scale and Diversity of the Physical Technosphere: A Geological Perspective, The Anthropocene Review, 4, 9–22, 2017.